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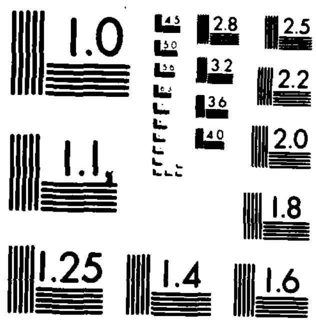

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AUTHOR: J. M. Ferritto

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This report presents data on the cost of seismic strengthening for a new concrete structure for two strengthening concepts: moment frame and shear wall. Damage is related to drift and acceleration of key elements of the structure. A damage matrix is constructed relating damage to design level and applied loading. An economic analysis is performed evaluating cost of strengthening, the present worth of expected damage, and the probability of site acceleration levels.

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CONTENTS

EXECUTIVE SUMMARY

PRESENT PRACTICE

Navy seismic design policy has utilized a probabilistic load level in designing some important new structures. An acceleration level equal to the site acceleration having an 80% chance of not being exceeded in 50 years has been used in the past for a few structures. This is equivalent to a 225-year return time acceleration. There is a policy for hospitals, however design levels apart from Uniform Building Code Specifications do not exist for most other structures. Present policy does not define what level of structural response should occur - should the structure remain elastic or should there be some amount of inelastic behavior?

THE PROBLEM

Design for the 225-year site acceleration often results in high seismic design levels which are difficult to achieve and are costly. The problem with the present Navy practice is that it does not clearly define a level of performance and safety of the structure because both the load, which has been defined, and the allowable deformation, which has not been defined, are necessary. Yet, despite the high design levels, a standardized risk or safety level is not being achieved. A complete specification of load and response is required so that a design procedure can be standardized. Further, it is necessary to distinguish the categories of important Navy structures that are mission essential and cannot tolerate an interruption in operation from those which, because of high occupancy or other important function, warrant increased expenditure to limit damage. Seismic design levels must be analyzed with consideration given to the expected damage from a site's seismic activity and the costs of seismic strengthening.

SUMMARY OF NCEL WORK

An automated procedure was developed for conducting site seismicity using the historical epicenter data base and available geologic data. This procedure permits definition of the site acceleration probability distribution, quantifying the seismic exposure.

This study has reviewed cost increases for construction strengthening and expected damage from seismic shaking. The specification of a 225-year return-time acceleration does not produce optimal least total cost designs over all ranges of acceleration; rather, the least total cost design acceleration varies with site activity. It is not economically advantageous to design against high ground acceleration. The economic analysis procedures specified in NAVFAC P442 for the cases studied suggest the present worth of future damage is low enough that an earthquake design return time lower than that presently used (for a ductility of 1.0) is more efficient.

In evaluating seismic planning decisions, it was recommended that the Navy should:

1. Adopt a risk pooling policy, that provides a direct linear relation between expected losses and cost of strengthening.

2. Consider as acceptable investments only those instances where the benefits exceed the costs.

3. Structures serving a mission that requires them to be functional after an earthquake should be identified when the project is initiated. The user/resource sponsor should be asked to state the desired level of resistance. Levels of resistance for medical facilities are discussed in DM-33.2 and 33.3. Critical structures as defined below warrant a high level of resistance.

In addition to facilities serving a special military function, those that would aid recovery or protect life should be considered essential (fire stations, utility systems, crash and rescue facilities, telephone facilities). Levels of resistance are discussed below under definitions.

Other important structures that are considered to be essential facilities should be analyzed in terms of economics of strengthening and replacing damaged contents. These structures usually fall in the following categories:

a. Structures housing a large number of people (theatres, etc.).

b. Structures housing expensive equipment (computer centers, etc.).

This work is reported in NCEL Technical Report R-885.

To further develop the seismic economic analysis techniques and obtain more accurate data, a structure typical of Navy construction was selected for a detailed study. The structure was a three-story frame building built on the east coast for which detailed cost data and plans were available. Three methods of seismic strengthening were considered for the steel structure: moment frame, braced frame, and frame/concrete shear wall. Two methods were considered for the concrete structure: (1) moment frame and (2) moment frame and shear wall. Designs of each method were prepared for six levels of loading from 0.1 to 0.35g. Designs were set at a ductility of 1.0, which (1) allows for elastic analysis techniques to be utilized, (2) permits response to be related to other ductilities, and (3) offers the engineer the simplest dynamic analysis technique. Each design was then analyzed for a series of seismic levels and damage at each level evaluted. An economic analysis was then performed using the cost data, damage data, and seismic probability distributions from five sites. Results are discussed in this text and also in NCEL Technical Note N-1640.

In order to consider implementation of this work, it is recommended that the following definitions be adopted to clarify Navy requirements:

1. <u>Critical Structures</u>. Those housing hazardous substances whose release is liable to cause a catastrophe. These structures should be designed to resist the maximum probable earthquake which is likely to occur at the site.

2. Mission Essential Structures. Those serving a military mission which requires them to remain functional after an earthquake. User/resource sponsor to identify requirement and appropriate level of resistances.

3. Other Essential Structures.

A. Very Important Structures. Those limited number of facilities warranting special attention to minimize damage and reduce the risk of loss of life and for which additional expenditure of funds is justified.

B. Important Structures. Structures which require designs in excess of code provision but do not have the same level of importance as above. Optimal level of expenditure of funds is considered, minimizing the expected costs, damage, and strengthening.

4. Ordinary Structures. The majority of structures for which a dynamic analysis is not required, and building code provisions are adequate.

Seismic strengthening costs are dependent on the type of strengthening system utilized; damage is caused both by drift and acceleration. It is important to note that strengthening usually limits drift damage but also usually increases acceleration damage. Damage to a structure is a complex mechanism influenced by damping level, degree of inelastic behavior, acceleration level as well as drift level, and spectral region of response. Economic design levels appear to be somewhat greater than those indicated by building codes; however, design for the full 225-year acceleration would not be cost-effective for all cases. The most cost-effective design acceleration is a function of construction type and site seismic exposure.

Acceleration produces a significant amount of damage, and special care should be taken to design ceilings and lights to withstand acceleration. Shaking produces overturning of equipment, which is a significant factor, accounting for most mechanical and electrical losses.

RECOMMENDATION

Critical Mission Essential Facilities. Identify required levels of performance, perform deterministic analysis for continuing operational capability under maximum credible event.

Very Important Structures. Design for 225-year return time acceleration.

Important Structures. Design for 60- to 100-year return time but not less than building code requirements.

For each of the above a dynamic analysis is required. For the Very Important and Important structures the required level of performance shall be:

Ductility = 1.0

that is, a structure at the beginning of plastic deformation. The required analysis technique shall be an elastic dynamic analysis utilizing either response spectra or a series of time histories. In the selection of earthquakes used in developing the spectra or time histories, consideration shall be given to matching expected site soil conditions, earthquake magnitudes, and separation distances. It is important that the frequency content of the excitations accurately represent the causative earthquakes (magnitudes and distances) as well as the soil filtering (site conditions). NCEL has developed techniques for this as noted in Technical Report R-885. Consideration shall be given to events local and distant to the site since substantial variation occurs in the frequency content.

For the recommended design levels for Important buildings, it is estimated that class of structure should see 20% building damage with a probability of a fatality of 7×10^{-5} per person exposed per year over a 50-year exposure.

INTRODUCTION

The United States Navy has numerous bases located in active seismic regions, and each of these bases resembles a small city containing work areas and residential areas. With any seismic plan, establishing appropriate design levels which are safe, consistent with established knowledge, and economically effective must be considered. Because of the limited amount of available construction funds, an investigation of the economics of seismic strengthening is appropriate. What level of seismic design should be utilized considering costs of strengthening, the expected damage, and loss of life? This complex problem is the topic of this report.

Previous reports (Ref 1 and 2) present a detailed discussion of the state-of-the-art of seismic design and damage evaluation for a steel structure. This document will draw upon that information and develop an economic analysis of seismic design for a concrete structure. Earlier results (Ref 1) using preliminary data indicated that designing for high levels of ground motion might not be cost-effective. To further explore this problem a typical structure was selected for detailed study. The structure chosen was representative of a class of structures utilized by the Navy for administration, light industrial work, or living quarters.

The structure selected was an actually constructed three-story building for which detailed cost data and drawings were available. The building was recently constructed at an eastern Navy base in a nonseismic area. Thus, the nonseismic starting condition was established. The building was a frame structure, 185 by 185 feet in plan. The Appendix shows both the plan (Figure 17) and elevation views of the building (Figure 18). The latter also indicates the framing of the building. Reference 2 included an economic analysis for a steel structure; this report will analyze the building as a concrete structure.

SEISMIC DESIGN

The selected structure was redesigned considering the structure to be new construction and being located in seismically active areas. Seismic design concepts were typical of conventional West Coast standard engineering design practice.

The structure was designed for six levels of peak ground acceleration: 0.10 to 0.35g with 0.05g increments. Elastic design spectra utilizing Newmark standard spectral shapes were utilized. Two concepts of seismic strengthening were utilized: (1) moment frame and (2) shear wall. The performance level of the structure under the specified spectra was required to be a ductility equal to 1.0 design, such that members were to be at yield. This performance level was specified for several reasons. First, specifying a ductility of 1.0 is the same as specifying a higher acceleration and some ductility greater than 1.0. Second, use of a ductility equal to 1.0 allows the structural design engineer use of all elastic computer codes without need for a nonlinear analysis; further, nonlinear spectral techniques need not be used.

The required designs for the two concepts of strengthening and six load levels were performed under contract with a firm having significant experience in seismic design. As part of that effort, the contractor was also tasked to provide detailed cost estimates for seismic strengthening by treating the structure as new construction, using the available cost data on the existing structure, and making adjustments for West Coast construction practice. Results of the designs are presented in Reference 3.

Cost of Seismic Strengthening

Detailed structural costs were estimated based on the results of the six design cases for the two concepts of strengthening. The cost of the existing exterior frame construction was deducted from the total building cost, and then each new seismic framing system was added to obtain a new total building cost. Concrete or masonry seismic shear wall configurations, when utilized, were assumed to replace the existing 6-inch concrete block. Foundation redesign was included. Costs were adjusted to 1981 costs in the Los Angeles area. Figure 1a shows the seismic strengthening concepts; Figure 1b shows the increase in cost for seismic strengthening. Cost-estimating details are given in Reference 3. Figure 2 gives the first mode periods of the structure for the two strengthening concepts as a function of design level. The moment frame period shows greatest variation with design acceleration.

Damage Evaluations

Damage to structural frame members, shear walls, and other elements associated with displacement are influenced by the interstory drift. Other elements tied to the floors, such as equipment or contents, are influenced by floor acceleration. Reference 1 is a detailed study of previous work in damage evaluation and will not be repeated here.

To evaluate the damage expected to the structure, each of the six design levels for each of the two design concepts of strengthening was analyzed for a series of applied seismic load levels. Nonlinear finite element techniques were employed. The program DRAIN-TABS was utilized to perform the analysis. Figure 3 gives the damping used for the analysis based on engineering practice; damping increased with the ratio of applied load to design level. Drift and floor-acceleration time-history responses were computed in the analysis. Effective response levels were selected at 65% of peak values and used in the damage prediction. The value of 65% has been used in past studies to approximate effective peak ground acceleration. This value, based on engineering practice, is used to reduce the peak values to a level of repeated sustained loading.

The detailed cost estimate was utilized to identify key elements of the structure to which dollar values could be associated. Repair factors for damage were estimated. The key elements were divided into drift- or acceleration-sensitive components, and values of drift and acceleration were then related to damage for each element.

Tables 1 and 2 g've the damage ratios for each key element. It should be [illegible]ted tha[illegible] value is included for contents and that a repair multiplier [illegible] o account for the added expense of post-earthquake

restoration. These can result in costs exceeding the total cost of the structure. This is reasonable since demolition and removal costs would be required for major repairs.

Use of Tables 1 and 2 in conjunction with the drift and acceleration values from the nonlinear analysis resulted in Tables 3 and 4 which present the damage matrices, giving damage as a function of design level and applied loading. Included in the damage matrix is the damage to the structure and the contents, using the noted repair factors.

Moment Frame. The response of the moment frame structure is in the constant velocity region of the spectra for all six design ranges. It is significant to note that as the structure is stiffened, displacement is reduced; however, acceleration is increased. Damage is dependent on both displacement and acceleration. Note also that for a given applied load level, each of the six design cases is at a different damping level, with the weakest structure being most heavily damped. In the low applied loading level, the strong structures are lightly damped, responding elastically with higher floor accelerations. The weaker structures are more heavily damped, responding inelastically with lower floor accelerations. In this range, stiffer structures receive greater damage; this condition exists to about 0.25g for the range of structures studied. Over 0.25g the stiffer structures exhibit lower damage, as might be expected. The use of a single time history event with its unique frequency content results in minor response variations. Any single time history has unique frequency gaps and high points. Since the period of the structure changes with strengthening, secondary interactions occur between the frequency high points and structure periods such that the responses at a particular design level might be slightly reduced or amplified over the response of an ideal time history without gaps and high points. Further, the six design cases are not exact multiples but rather depend on human selection of available structural shapes. These factors induce very minor dispersion in the results. A clear conclusion, however, is that stiffening in the low applied acceleration region does not reduce total damage. Figure 4 shows a plot of damage ratio as a function of applied load to design level. The data illustrate the effects of variation in period of the structure on the response. The damage ratio is a complex function of period, damping, range of nonlinear behavior, and the mix of total damage caused by drift and acceleration.

Shear Wall. The shear wall/frame structure was stiffer than the moment frame. Damage (including components) was generally less with this structure. In general, because of the low period of the structure, floor acceleration resulting from amplification of base motion was less and in high applied acceleration load levels, attenuation occurred. Figure 5 shows a plot of damage ratio as a function of applied loading.

Site Seismic Probability

An automated procedure has been developed at NCEL to perform a seismic analysis using available historic data and geologic data. The objective of the seismicity study was to determine the probability of occurrence of acceleration at the site. To do this, site coordinates and the study bounds are specified in terms of latitude and longitude.

A regional study is first performed in which all of the historic epicenters are used with an attenuation relationship to compute site acceleration for all historic earthquakes. A regression analysis is performed to obtain regional recurrence coefficients, and a map of epicenters is plotted. The regional recurrence can be used to compute the probability of site acceleration for randomly located events in the study area. Such a condition is used when individual faults are not known well enough to be specified.

When individual fault areas can be specified, individual subsets of the historic data are used in conjunction with geologic data to determine fault recurrence coefficients; these are used to compute the probability of site acceleration from individual fault sources. The total risk is determined for all faults specified. Confidence bounds are given on the site acceleration as a function of probability of not being exceeded. Results of five case studies were utilized in this work.

NAVY ECONOMIC ANALYSIS

Reference 4 specifies procedures for economic analysis of facilities. The principles of the analyses are to:

1. Insure an optimum allocation of scarce resources

2. Effectively consider alternatives and life-cycle funding implications

3. Recognize that money has value over time expressed by an interest rate

This analysis, thus, must include the consideration that earthquake strengthening is expressed as a current cost increase to protect against a future dollar loss. The real world is complicated by cost increases through inflation. This means that to repair or replace the damaged building some time in the future will cost more than today. The work in the previous sections expresses costs of strengthening and damage as a percentage of building value to maintain a common reference. That premise recognized increased value of the building and increased costs of repair. In an economic sense this may be expressed as letting the discount rate (the value of return on investment) be equal to the inflation rate.

The government has placed a value on money in time. NAVFAC P442 (Ref 4) and DODINST 7041.3 specify the discount rate as 10%. NAVFAC 442 states:

> "The rationale for adopting the private-sector rate of return as the discount rate for analyzing Government investment proposals turns on the notion that Government investments are funded with money taken from the private sector (preponderantly via taxation), are made in the ultimate behalf of the private sector (i.e., the individuals comprising it), and thus bear an implicit rate of return comparable to that of projects undertaken

in the private sector. In this interpretation, 10% measures the opportunity cost of investment capital foregone by the private sector."

The 10% rate is a differential rate in addition to inflation.

When the present worth of the annual expected damage is considered using a discount rate of 10%, the present worth estimate of the damage would effectively be reduced by a factor of about five. To restate this, the earthquake could occur at any point during the life of the structure; the best estimate is to consider an equivalent series of annual expected losses. The assumed life of the structure is 50 years,* based on Naval Facilities Engineering Command (NAVFAC) seismic design criteria. The present worth of this accumulated loss series can be computed, and its value is about one-fifth of the total expected loss.

It is important to note that the discount rate specified for use is actually a differential rate of 10% over the rate of inflation. It is recognized that the future cost of the repair would increase with time. One could use the differential rate and not consider inflation, or one could consider the rate of inflation to project an increased repair cost and then discount that cost using a discount rate of 10% plus the inflation rate. The results for modest inflation rates are approximately the same. The differential cost approach has been used in this study.

Included in the economic analysis is a value for injury and loss of life. This is discussed in depth in Reference 1. The value of loss of a life used in the analysis is $300,000. As discussed later, results were not sensitive to the value selected.

SITE STUDIES

Five sites** were examined in light of the cost and damage data presented earlier and the probability of site acceleration distributions. Figures 6 and 7 give the results of the increased total cost of strengthening for each structure type at various design levels where total cost includes both seismic strengthening and expected damage. The moment frame is the most expensive strengthening system and demonstrates clearly a minimum cost. Costs for the braced frame and shear wall systems do not vary as significantly with design level.

Based on the probability distribution data from the five sites, Figure 8 indicates the least-cost design acceleration in terms of the 225-year return-time acceleration (80% probability of not being exceeded in 50 years).

*Reference 4 usually uses 25 years for performing economic analysis. Use of 50 years was selected to conform to seismic criteria in use.

**Bremerton, Wash.; Memphis, Tenn.; San Diego, Calif.; Port Hueneme, Calif.; and Long Beach, Calif.

Reference 2 discusses use of a penalty factor of five applied to damage estimates for "very-important" facilities to which added expenditures can be justified. The reader is also referred to Reference 2 for an in-depth discussion of classification of facilities into categories. Use of a penalty factor of five results in the data in Figure 9.

DISCUSSION

Seismic strengthening costs are seen to be dependent on the type of strengthening system utilized; damage is correlated both to drift and acceleration. Strengthening alone limits drift damage but increases acceleration damage. Damage to a structure is a complex mechanism influenced by damping level, degree of inelastic behavior, acceleration level as well as drift level, and spectral region of response. Economic design levels appear to be somewhat greater than those indicated by building codes; however, design for the full 225-year acceleration would not be cost-effective for all cases. The most cost-effective design acceleration is a function of construction type and site seismic exposure.

Acceleration produces a significant amount of damage, and special care should be taken to design ceilings and lights to withstand acceleration. Shaking produces overturning of equipment, which is a significant factor, accounting for most mechanical and electrical losses. Since stiffening produces increased acceleration, consideration should be given to development and utilization of isolation techniques.

Several seismic design options were presented in Reference 2 for NAVFAC consideration. One option was use of the full procedure for conducting an economic analysis. Another simply suggested economic design return time acceleration levels. This latter approach is most easily implemented and is suggested for use.

For the class of important buildings a value of design acceleration with a 60- to 100-year return time appears to be reasonable. Figure 10 shows the relationship of return time to probability as a function of building life. A 100-year return-time acceleration would have a probability of not being exceeded in a 50-year exposure of 0.62. Figure 11 shows the relationship of acceleration to the 80% probability acceleration of not being exceeded in 50 years. These data are based on a composite of a number of sites studied. Figure 12 shows a histogram of the probability distribution of acceleration. Use of a 100-year return-time acceleration would represent a design level of about 70% of the 225-year return-time level, and 60-year return-time acceleration would be about 50% of the 225-year return-time level.

An examination of the computed results of the probabilistic damage analysis over the life of the structure shows that most damage comes from the exposure to low level acceleration. Structures which respond elastically in this range being designed for high acceleration exhibit high floor accelerations which cause much of the damage.

Figures 13, 14 and 15 show a histogram of the distribution for a typical site with a 225-year return-time acceleration of 0.25g. Also shown in these figures is the damage ratio for steel-moment-frame, concrete-moment-frame, and concrete moment frame and shear wall construction. As noted, strengthening produces little or no reduction

in damage at low acceleration levels, which are most probable because floor acceleration increases from the resulting stiffening of the structure.

Although not part of the scope of this task, some conclusions can be drawn on upgrading existing construction. The seismic upgrade of existing construction differs from new seismic design in that the presence of an existing structure forces the upgrade to be incremental in nature, applying units of additional strengthening to improve an existing structure rather than a more continuous set of alternatives in new construction design such as column size or shear wall thickness. The cost of seismic strengthening of existing construction must be greater than those of new construction; and probably since the strengthening takes place as an add-on repair or alteration, its effectiveness will be less than that of new construction. Thus, as a general conclusion the level to upgrade existing construction cannot be greater than that of new construction.

There are several important considerations in determining upgrade levels for existing construction:

(1) Level of initial seismic design

(2) Occupancy level and building importance

(3) Remaining useful life

It is clear that, for short-lived facilities, those of low occupancy or low importance, and those where the expected damage is low, seismic upgrading should not be undertaken until higher priority structures are upgraded. The decision of upgrading of existing facilities is complicated by the variations in types of construction, initial seismic design level, condition of the structure, and site seismic hazard. Reference 5 presents a procedure for the economic analysis of upgrade levels for existing construction.

In the weighting of alternative levels of seismic upgrade, points contributing to higher upgrade design levels include the level of seismic exposure and the equivalent building population. Points reducing the level of seismic upgrade include the existing seismic design level or the level of expected damage. A weighting system can be constructed to produce a building score. This score could be related to the useful life to determine the extent of the upgrade, with full upgrade being equivalent to that of new construction. A point for consideration is whether partial upgrading is cost-effective. For upgrade projects the cost of mobilization may be high such that levels of upgrade less than, say, building code level may not be economically different than a full building code level, and expected damage may not be significantly reduced.

RECOMMENDATION

For new construction the following guidelines are suggested.

Structure	Design Level
Ordinary Building	Uniform Building Code
Important Building	60- to 100-year Return-Time Acceleration*
Very Important Building	250-year Return-Time Acceleration*
Critical Mission Essential	Maximum Credible Acceleration

The accelerations should be obtained from a site seismicity study using available historic data augmented by geologic data. The site acceleration should be based on quantification of the risk from all faults within an area around the site capable of influencing the site response. Where faults are not defined regional analysis technique must then be used, quantifying the activity in tectonic structure of the site. Figure 16 from Reference 6 presents 100-year return-time acceleration for California and could serve as a basis for design for important structures.

Design of important structures for the 100-year return-time acceleration with a ductility equal to 1.0 should result in a maximum expected damage to the structure of about 20% and have an annual probability of a fatality of about 7.0×10^{-5} during the 50-year exposure.

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4. Command economic analysis handbook (revised Oct 1975), Naval Facilities Engineering Command, NAVFAC P442. Alexandria, Va., Oct 1975.

5. J.M. Ferritto. An economic analysis of seismic upgrading for existing buildings, Civil Engineering Laboratory, Technical Memorandum M-51-80-17. Port Hueneme, Calif., Jul 1980.

*But not less than the Uniform Building Code provision.

6. P.C. Thenhaus et al. Probabilistic estimates of maximum seismic horizontal ground motion on rock in coastal California and adjacent outer continental shelf, U.S. Geological Survey, USGS Open Field Report 80-924. Reston, Va., 1980.

Table 1. Damage Ratio From Interstory Drift for Reinforced Concrete

Element	Cost ($)	Repair Multiplier	Damage Ratios at the Following Interstory Drift --								
			0.001	0.005	0.010	0.020	0.030	0.040	0.070	0.100	0.140
1a. Rigid Frames	250,000[a]	2.5	0	0.02	0.03	0.08	0.18	0.32	0.75	0.90	
1b. Shear Walls	250,000[a]	2.0	0	0.05	0.30	0.30	0.60	0.85	1.00	1.0	1.0
2. Nonseismic Structural Frame	250,000	2.0	0	0.005	0.01	0.02	0.10	0.30	1.00	1.0	1.0
3. Masonry	417,000	2.0	0	0.10	0.20	0.50	1.00	1.0			
4. Windows and Frames	120,000	1.5	0	0.30	0.80	1.00					
5. Partitions, Architect. Elements	276,000	1.25	0	0.10	0.30	1.00					
6. Floor	301,000	1.5	0	0.01	0.04	0.12	0.20	0.35	0.80	1.0	1.0
7. Foundation	170,000	1.5	0	0.01	0.04	0.10	0.25	0.30	0.50	1.0	1.0
8. Building Equipment and Plumbing	731,000	1.25	0	0.02	0.07	0.15	0.35	0.45	0.80	1.0	1.0
9. Contents	500,000	1.00	0	0.02	0.07	0.15	0.35	0.45	0.80	1.0	1.0

[a]Varies with Design

Table 2. Damage Ratios From Acceleration

Element	Cost ($)	Repair Multiplier	Damage Ratios at the Following Floor Acceleration (g)				
			0.08	0.18	0.50	1.2	1.4
1. Floor and Roof Systems	301,000	1.5	0.01	0.02	0.10	0.50	1.0
2. Ceilings and Lights	288,000	1.25	0.01	0.10	0.60	0.95	1.0
3. Building Equipment and Plumbing	731,000	1.25	0.01	0.10	0.45	0.60	1.0
4. Elevators	57,000	1.5	0.01	0.10	0.50	0.70	1.0
5. Foundations (Slab on Grade, Sitework)	170,000	1.5	0.01	0.02	0.10	0.50	1.0
6. Contents	500,000	1.05	0.05	0.20	0.60	0.90	1.0

Table 3. Damage Ratios From Moment Frame

Applied Load (g)	Damage Ratio at the Following Design Acceleration (g) --						
	0.00	0.10	0.15	0.20	0.25	0.30	0.35
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.05	0.01	0.01	0.03	0.04	0.05	0.06
0.20	0.06	0.05	0.04	0.04	0.06	0.07	0.08
0.30	0.18	0.11	0.11	0.10	0.10	0.10	0.09
0.40	0.22	0.14	0.14	0.12	0.12	0.12	0.12
0.50	0.25	0.18	0.18	0.16	0.15	0.14	0.14
0.60	0.35	0.24	0.12	0.19	0.18	0.17	0.17
0.70	0.46	0.28	0.26	0.25	0.21	0.21	0.20
0.80	0.60	0.33	0.30	0.26	0.24	0.23	0.23
0.90	0.82	0.39	0.36	0.30	0.27	0.27	0.26
1.00	1.05	0.44	0.42	0.34	0.30	0.29	0.28

Table 4. Damage Ratios From Shear Wall

Applied Load (g)	Damage Ratio at the Following Design Acceleration (g) --						
	0.00	0.10	0.15	0.20	0.25	0.30	0.35
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.05	0.01	0.04	0.03	0.03	0.03	0.03
0.20	0.06	0.04	0.06	0.05	0.10	0.10	0.09
0.30	0.18	0.07	0.08	0.10	0.10	0.09	0.09
0.40	0.22	0.11	0.13	0.14	0.15	0.14	0.13
0.50	0.25	0.15	0.15	0.17	0.16	0.15	0.15
0.60	0.35	0.21	0.20	0.18	0.20	0.19	0.19
0.70	0.46	0.26	0.25	0.22	0.20	0.23	0.23
0.80	0.60	0.31	0.29	0.27	0.24	0.23	0.28
0.90	0.82	0.35	0.34	0.31	0.28	0.27	0.24
1.00	1.05	0.44	0.38	0.35	0.32	0.30	0.29

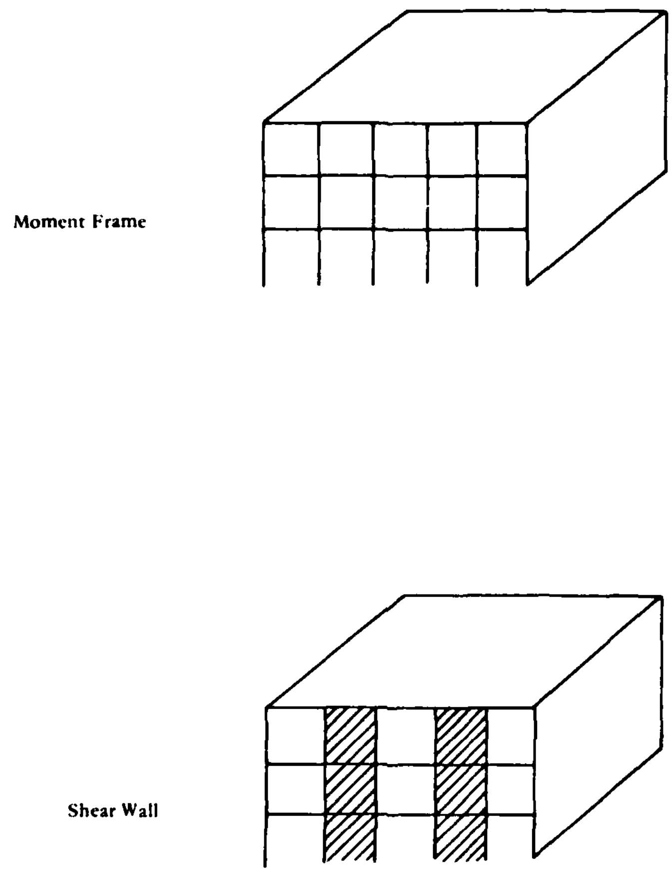

Figure 1a. Seismic strengthening concepts.

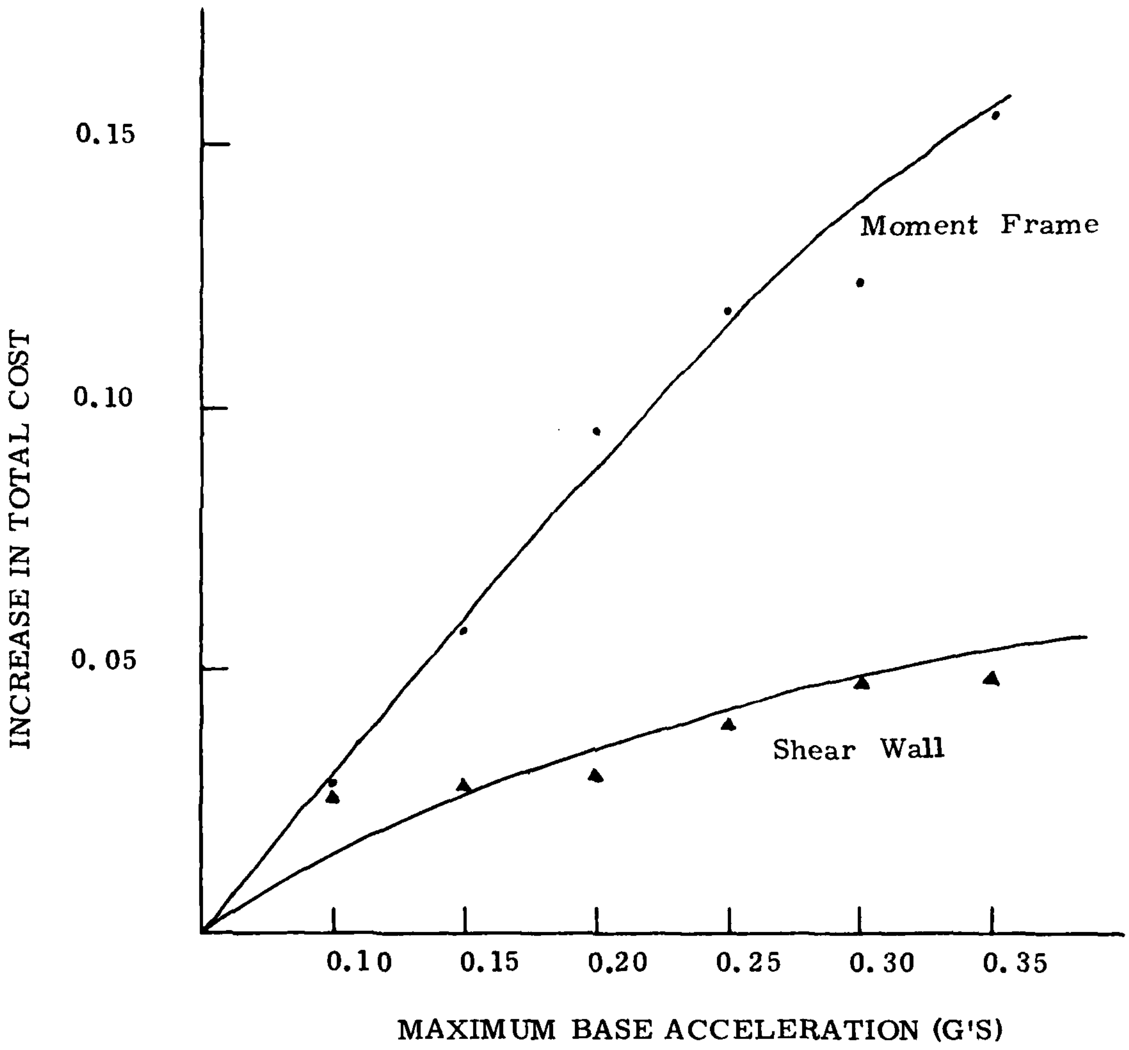

Figure 1b. Increase in cost.

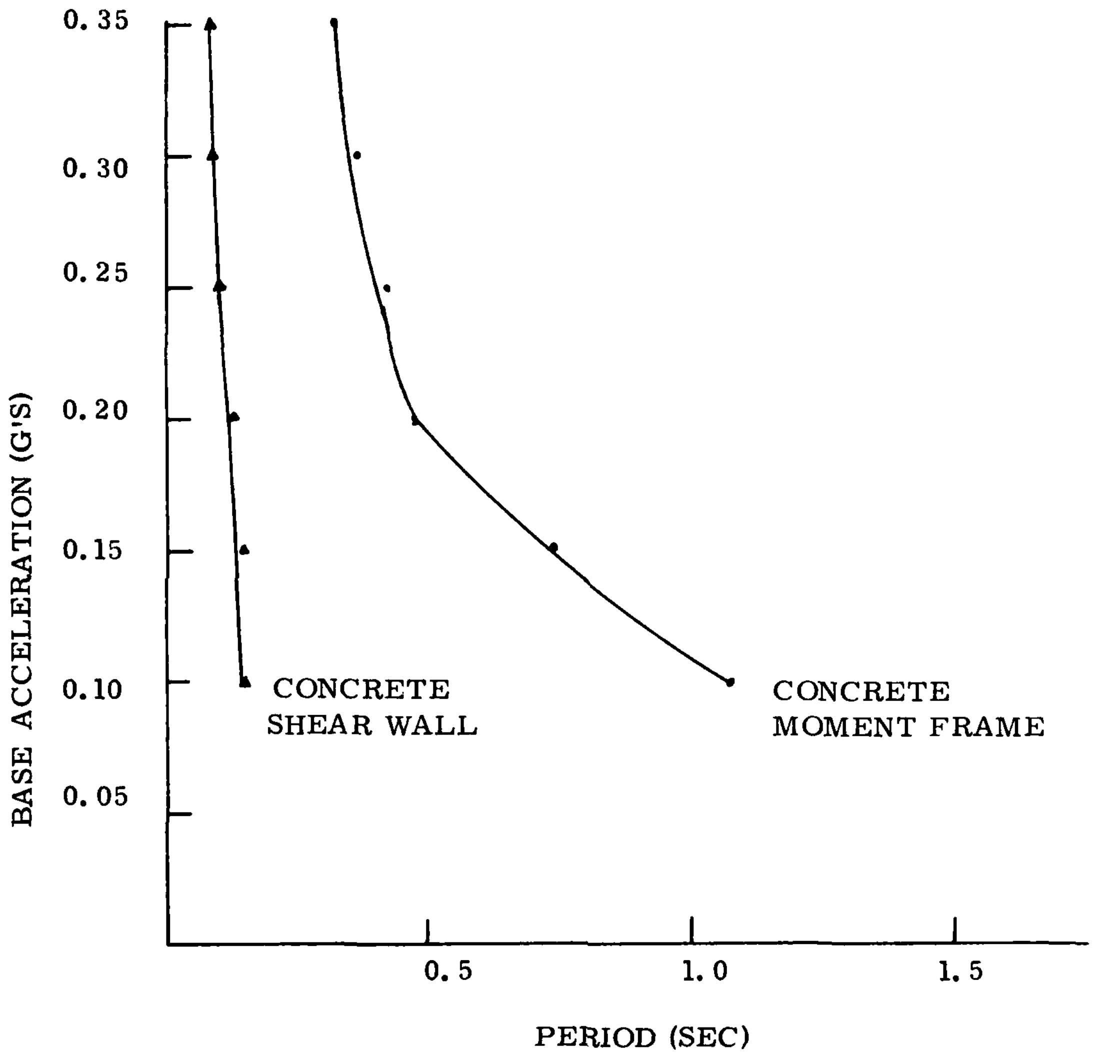

Figure 2. Fundamental period.

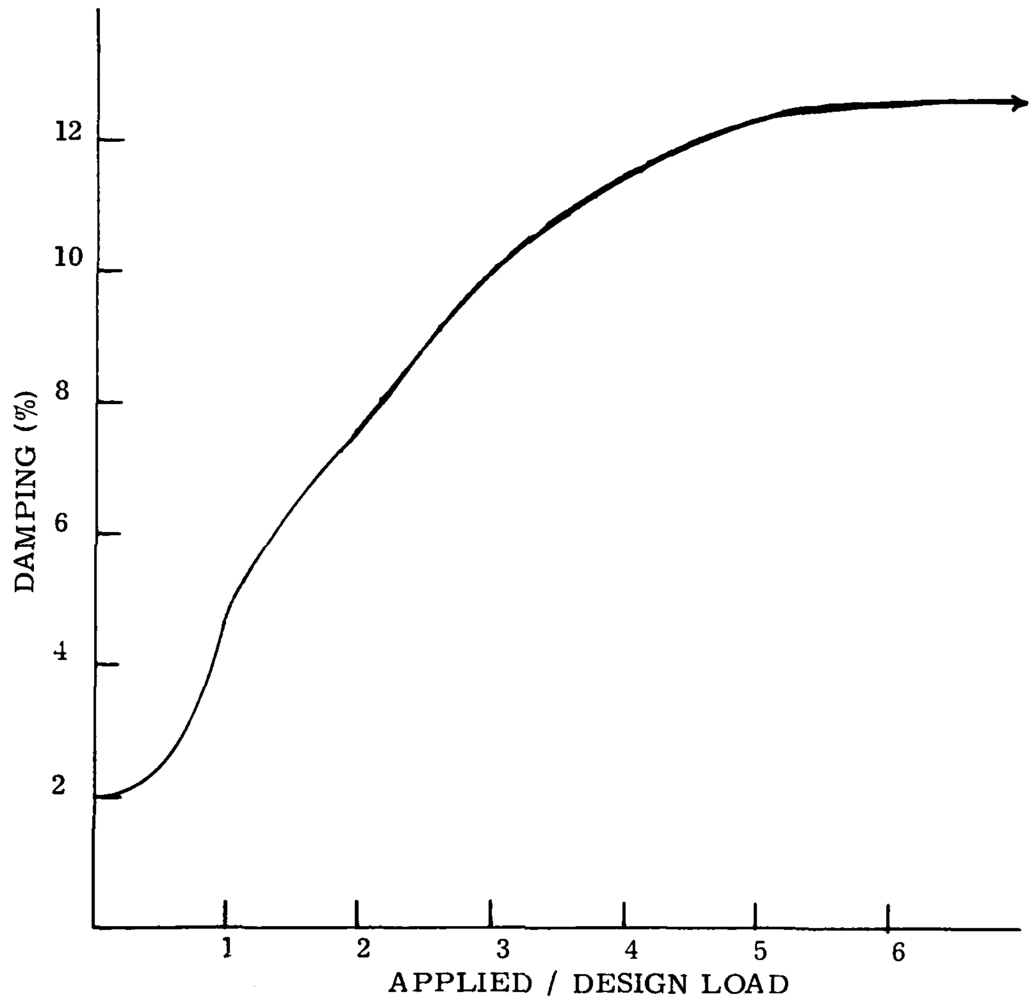

Figure 3. Damping concrete structure.

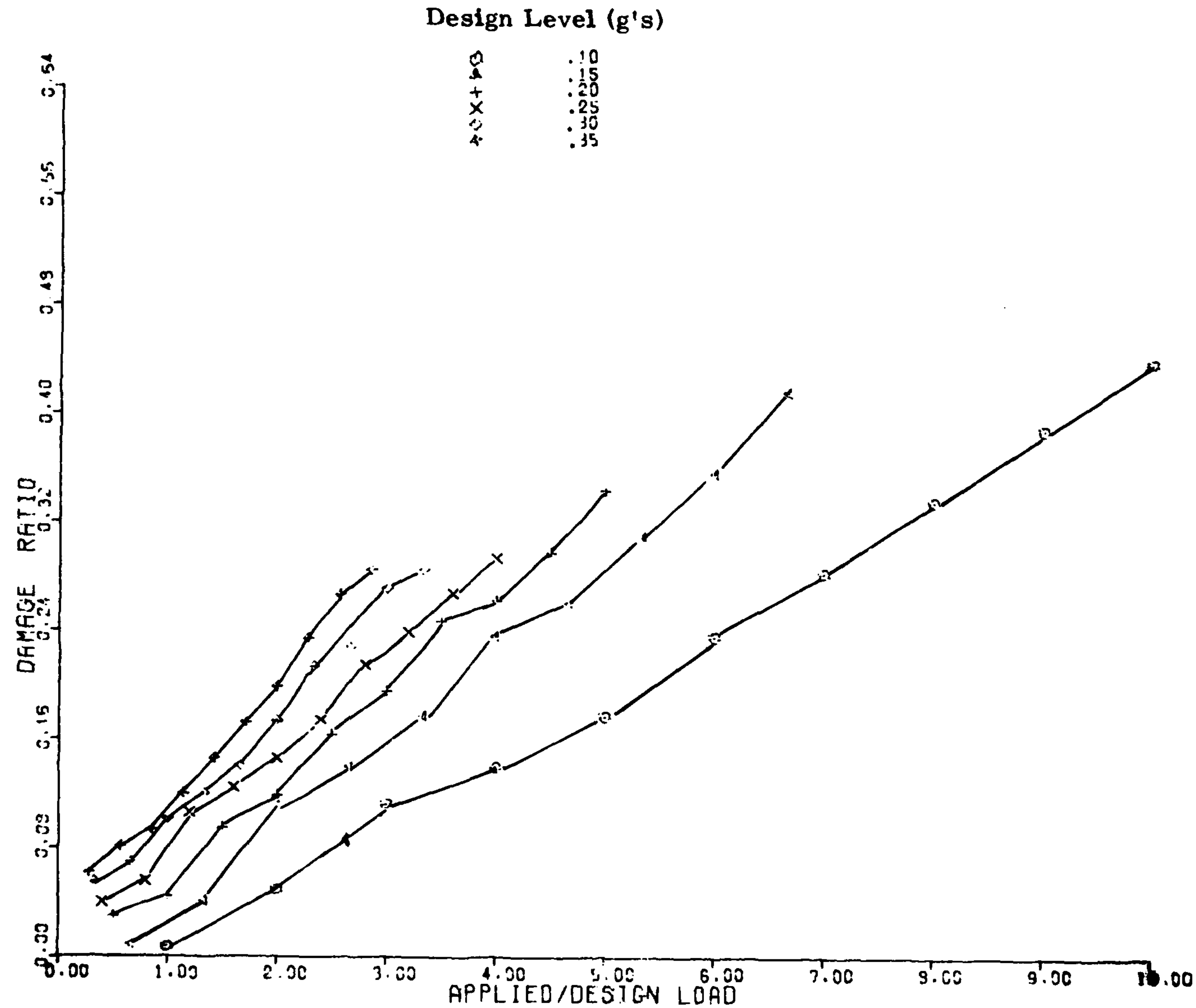

Figure 4. Damage ratio for concrete moment-resisting frame.

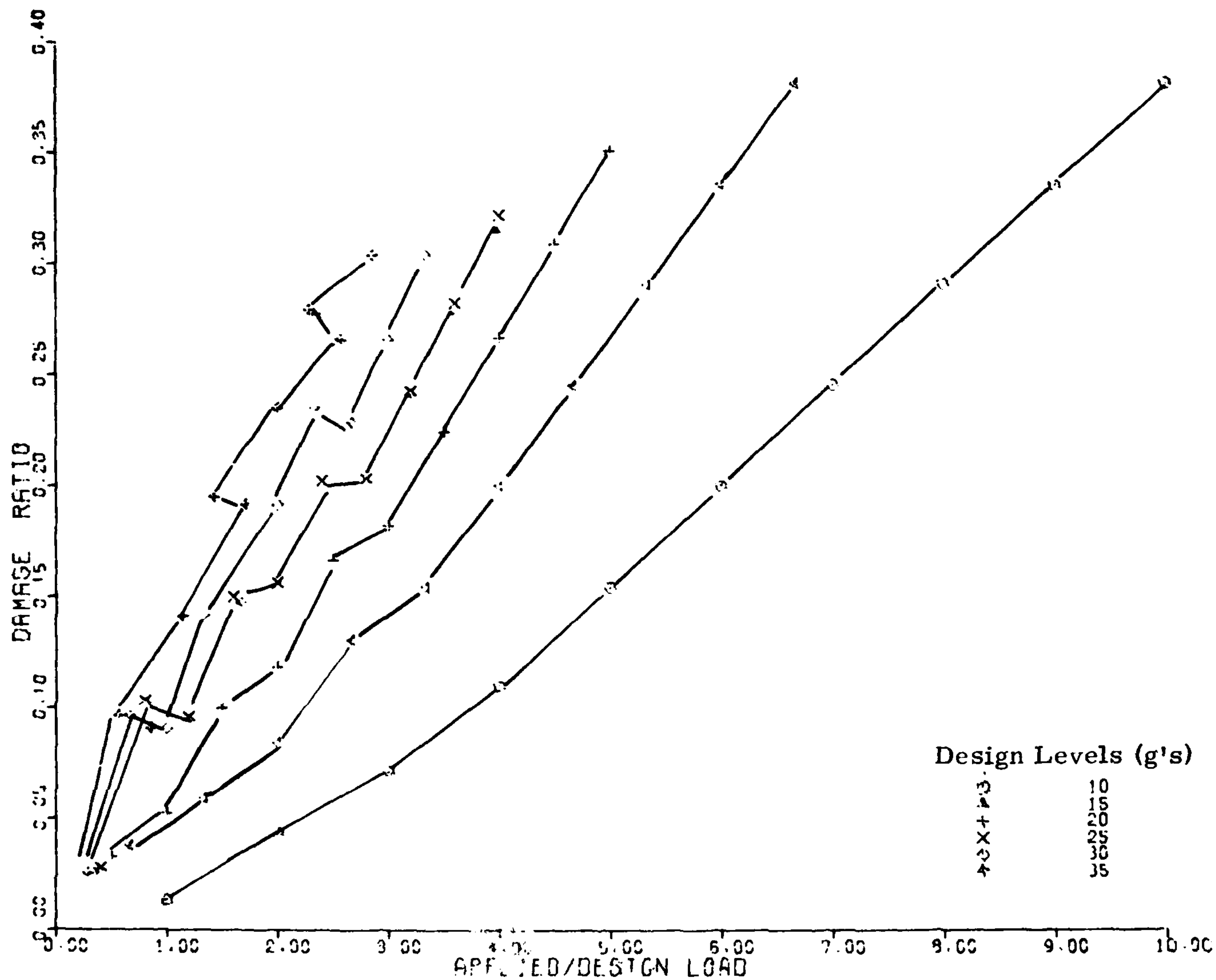

Figure 5. Damage ratio for concrete shear wall building.

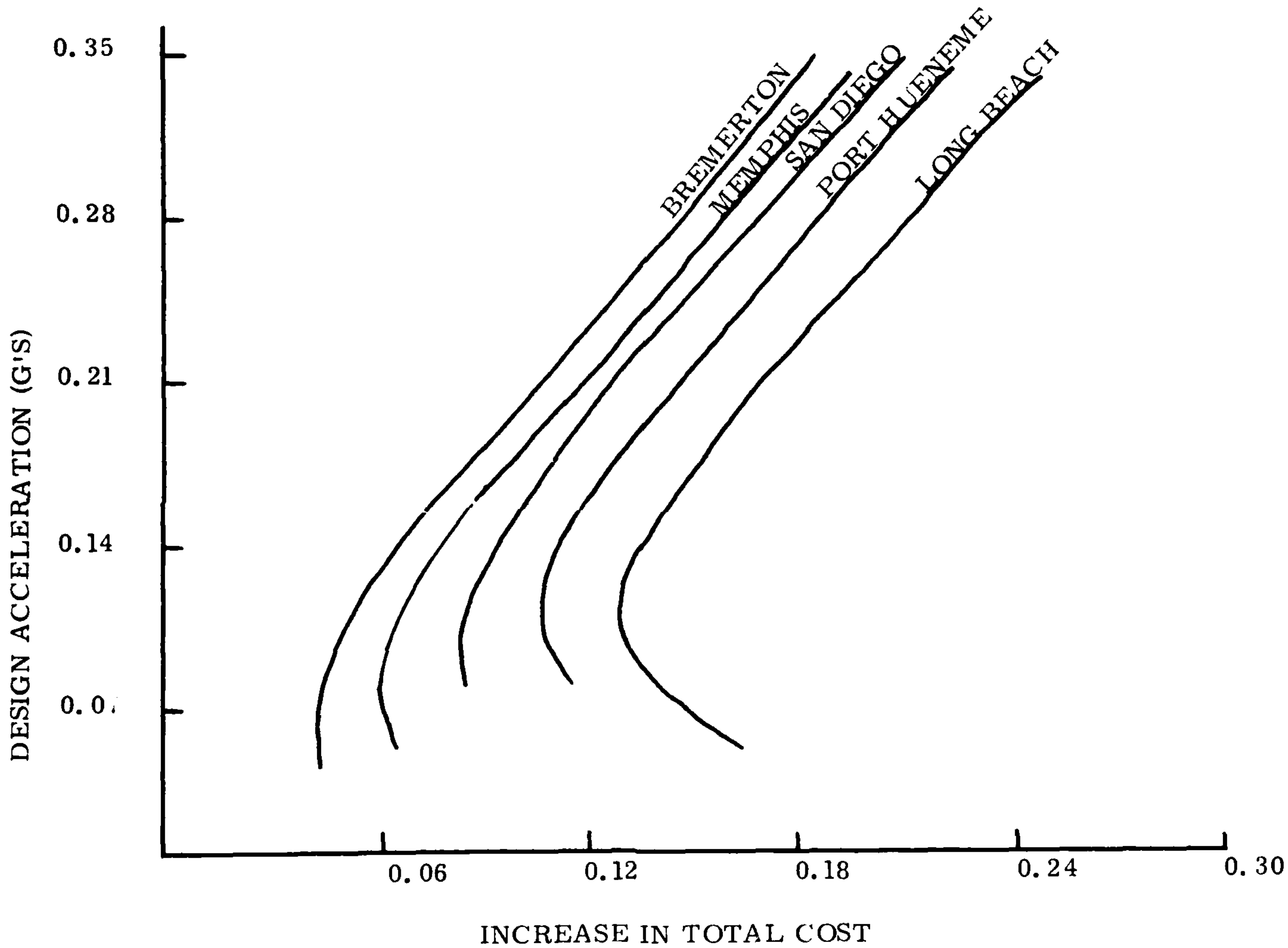

Figure 6. Seismic total cost for five sites, concrete moment frame (note that total cost includes seismic strengthening and expected damage).

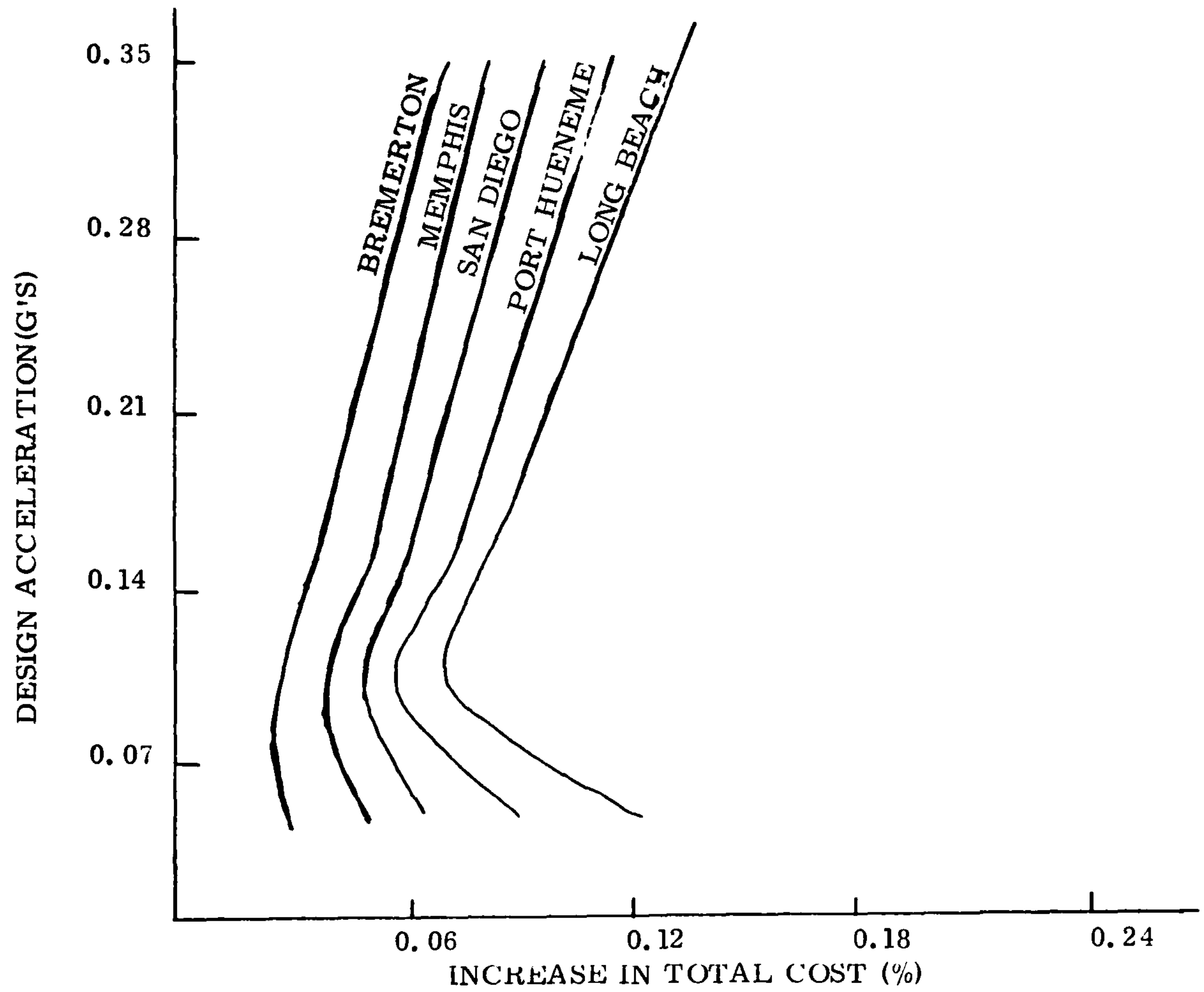

Figure 7. Seismic total cost for five sites, concrete shear wall building (note that total cost includes seismic strengthening and expected damage).

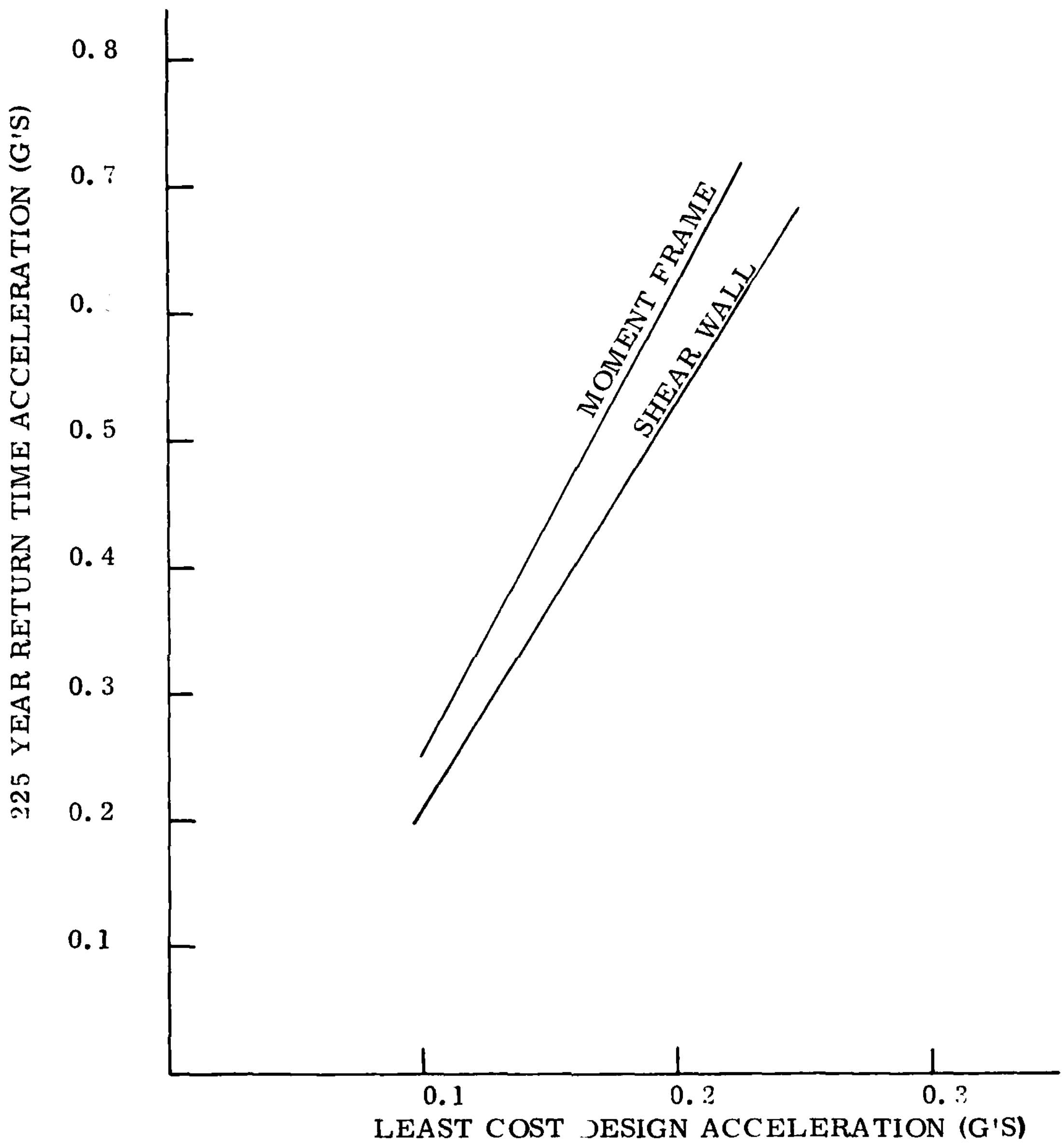

Figure 8. Least-cost design acceleration.

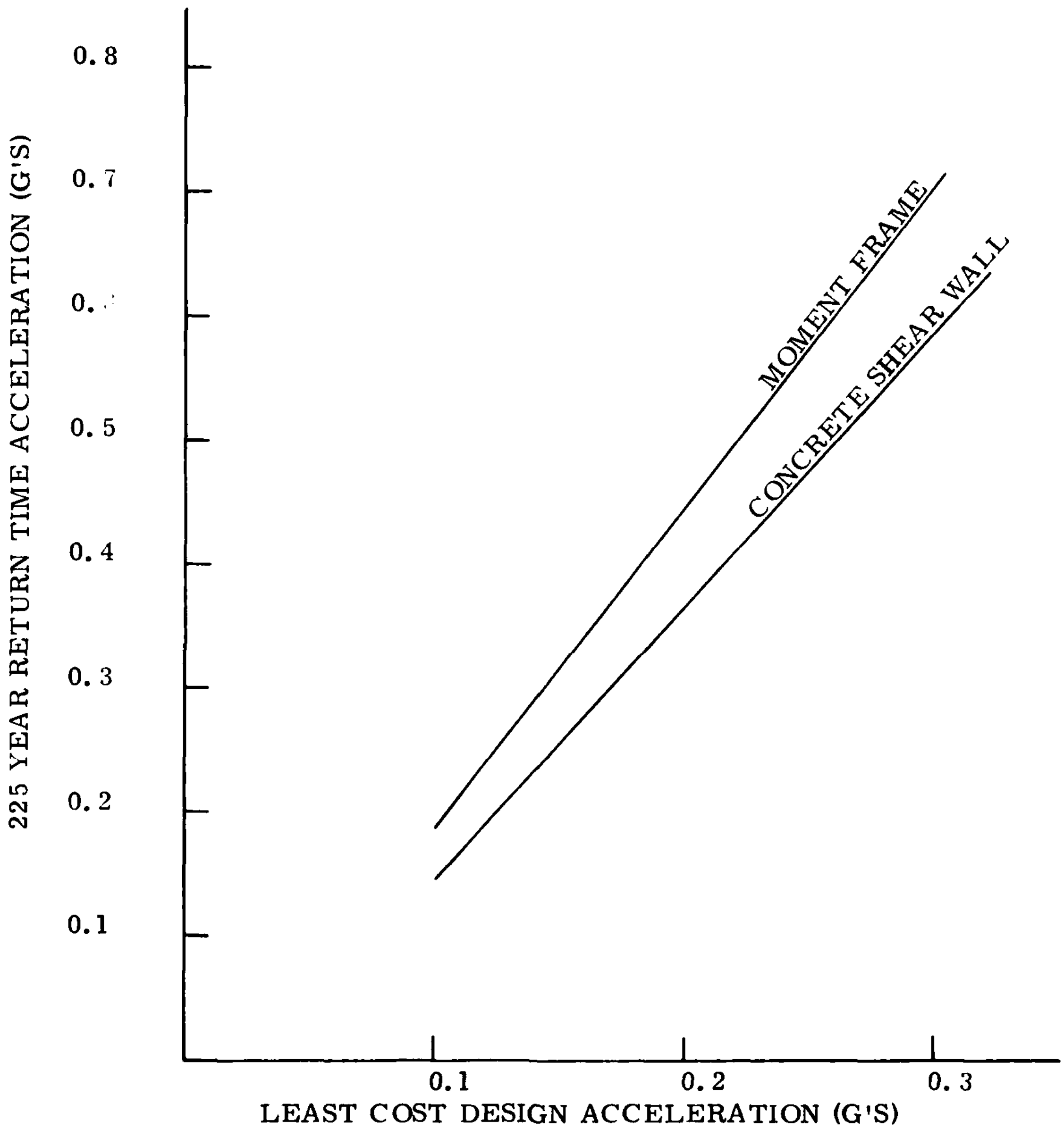

Figure 9. Least-cost design acceleration, very important building.

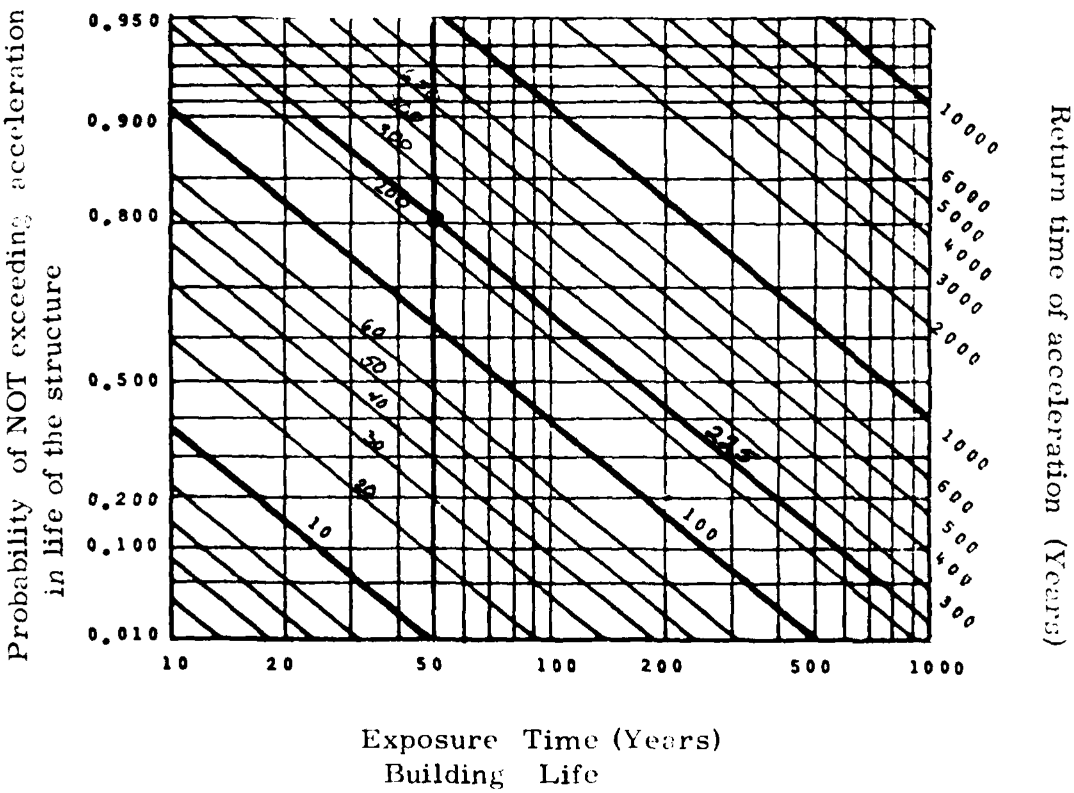

Figure 10. Relationship of probability to return time.

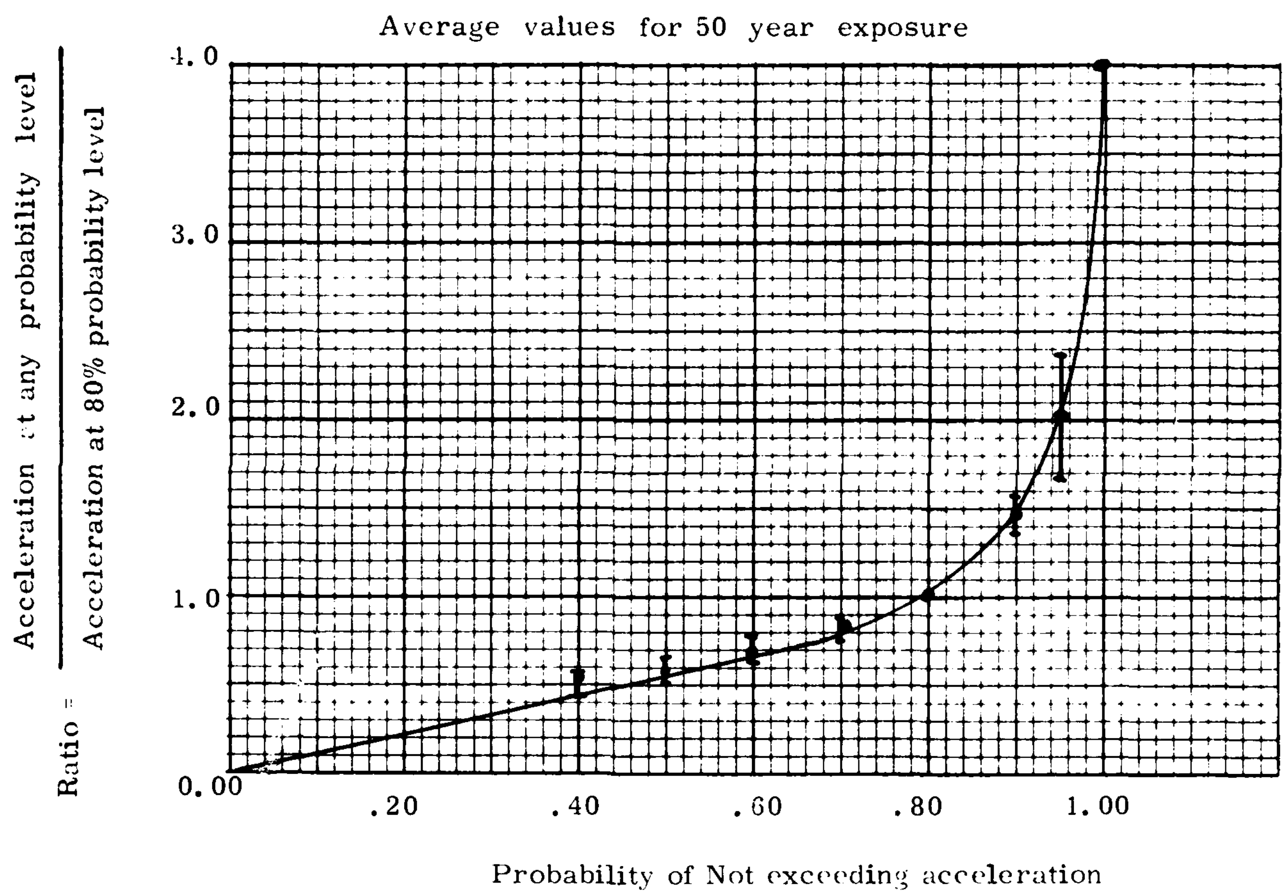

Figure 11. Relationship of acceleration at any probability to 80% probability.

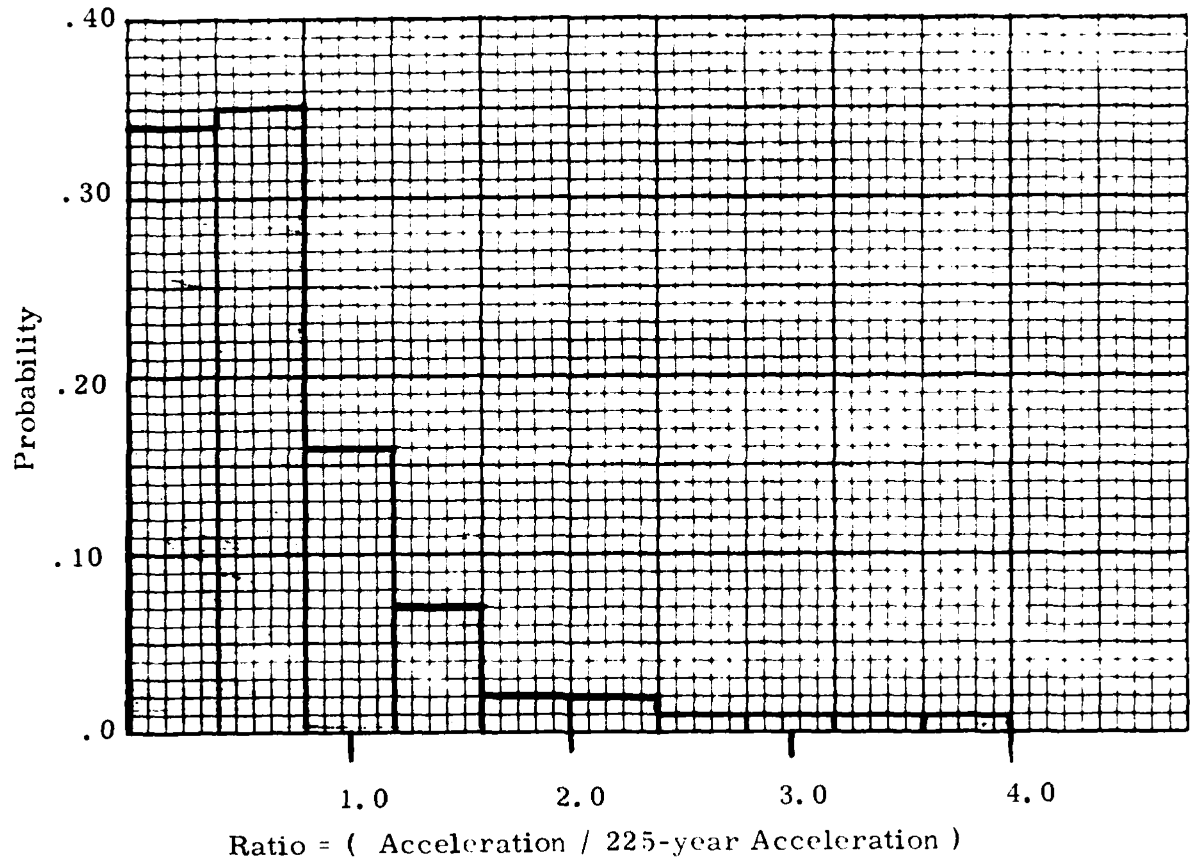

Figure 12. Histogram of probability distribution of acceleration.

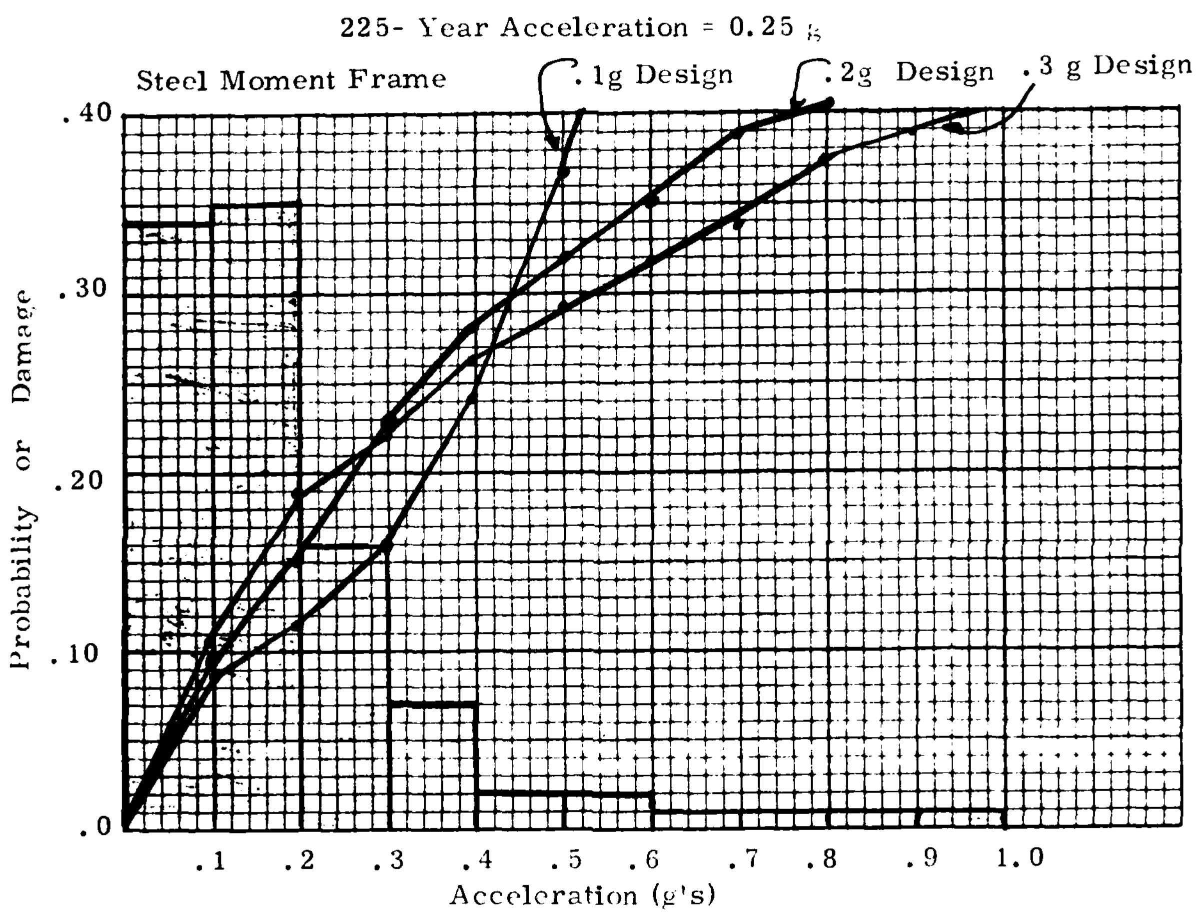

Figure 13. Histogram of probability distribution of acceleration and distribution of damage ratio with acceleration for steel moment frame.

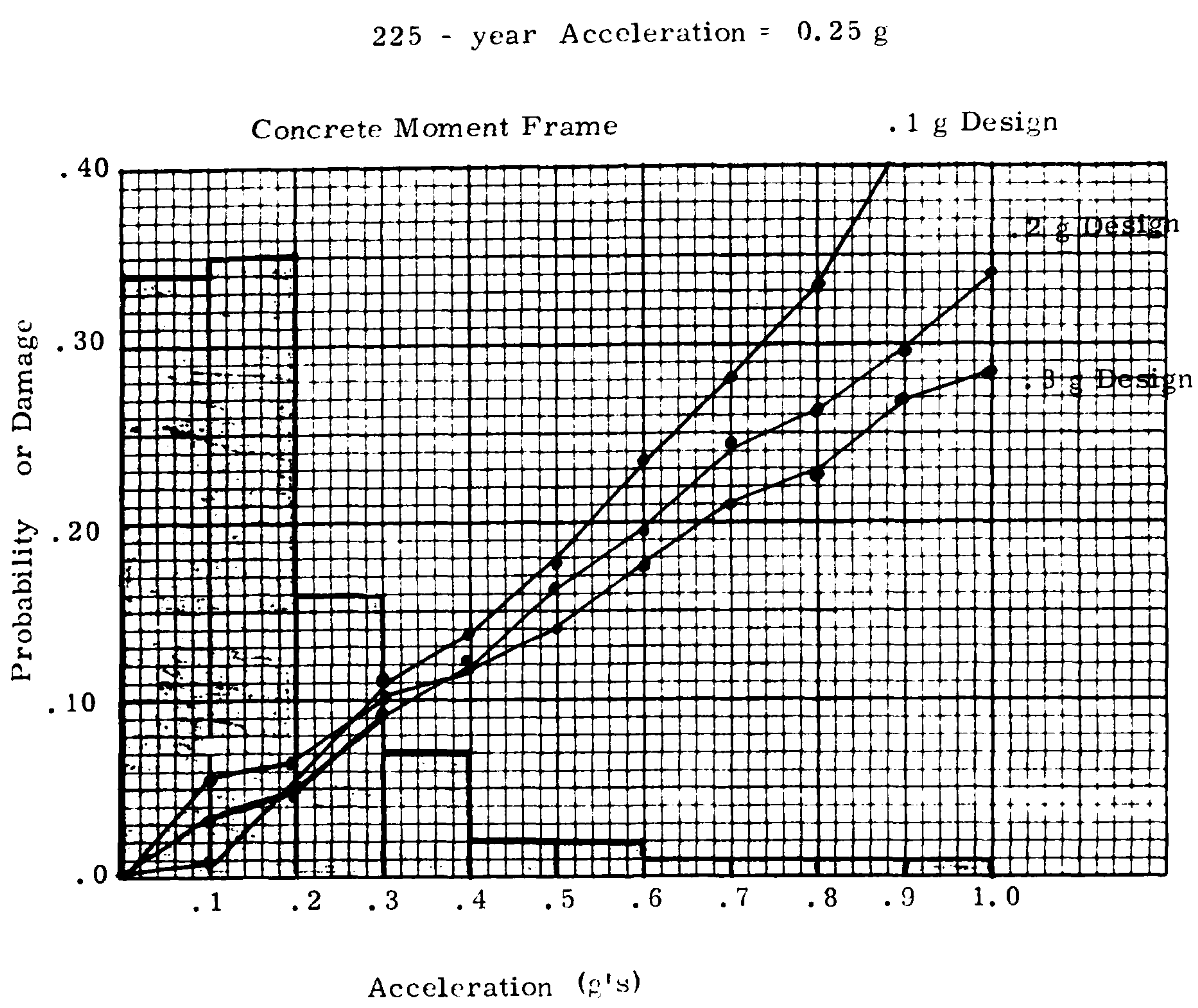

Figure 14. Histogram of probability distribution of acceleration and damage ratio distribution with acceleration for concrete moment frame.

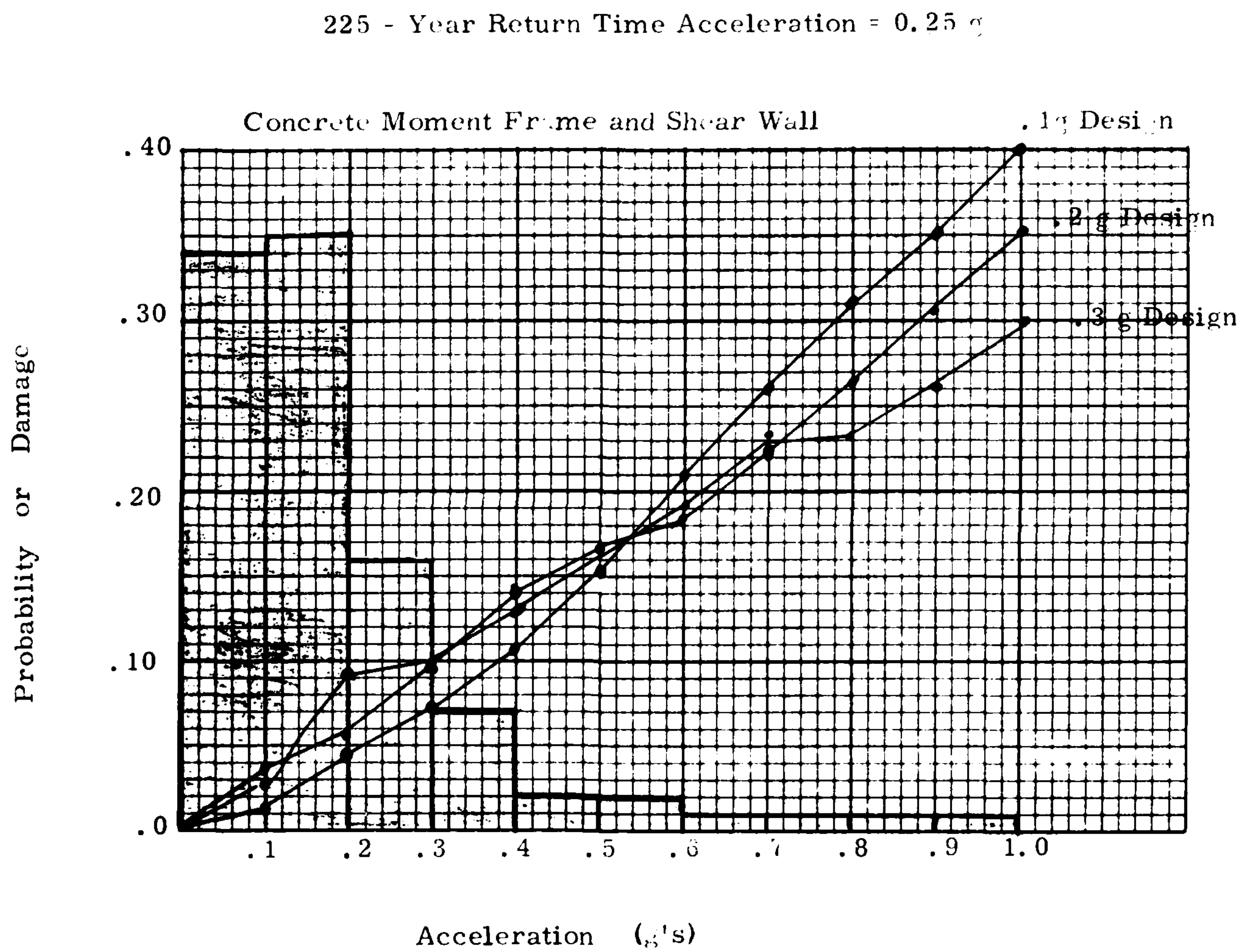

Figure 15. Histogram of probability distribution of acceleration and distribution of damage ratio with acceleration for concrete moment frame and shear wall.

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Ref (5)

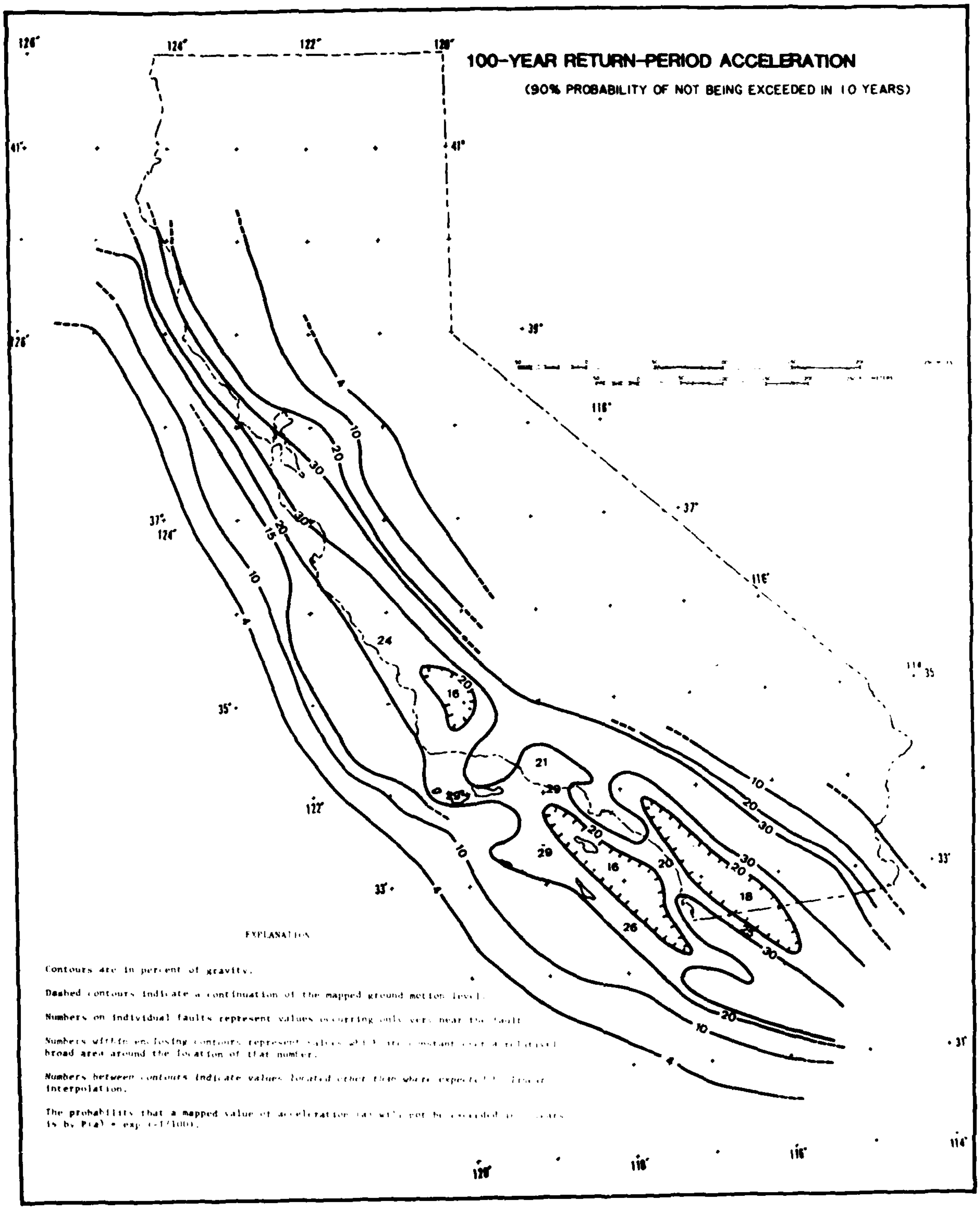

Figure 16. Recommended design level for class of structures defined as IMPORTANT (from Ref 6). Design to be ductility equal to 1.0.

Appendix

STRUCTURE PLAN AND ELEVATION

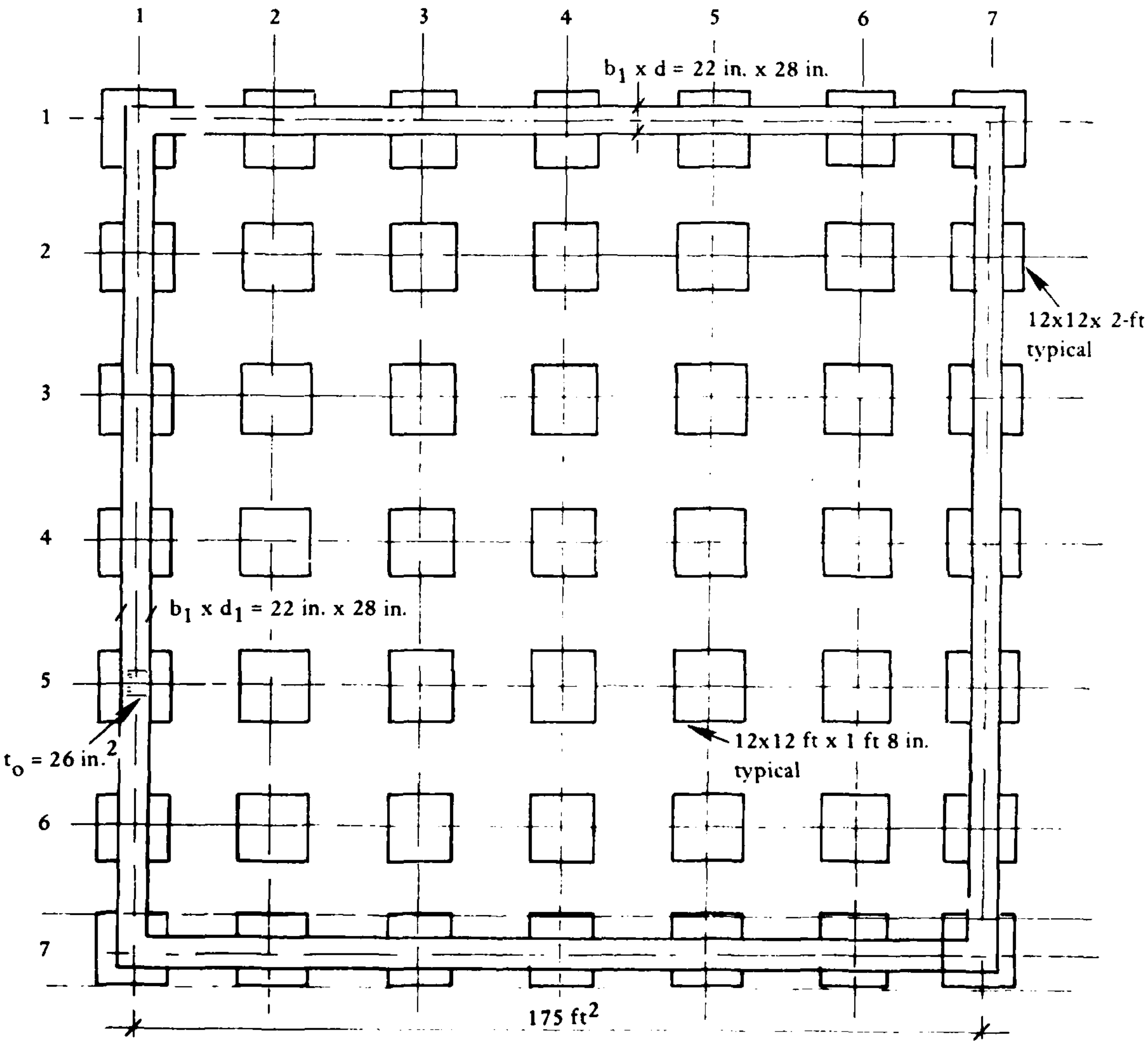

Figure 17. Foundation plan for moment frames.

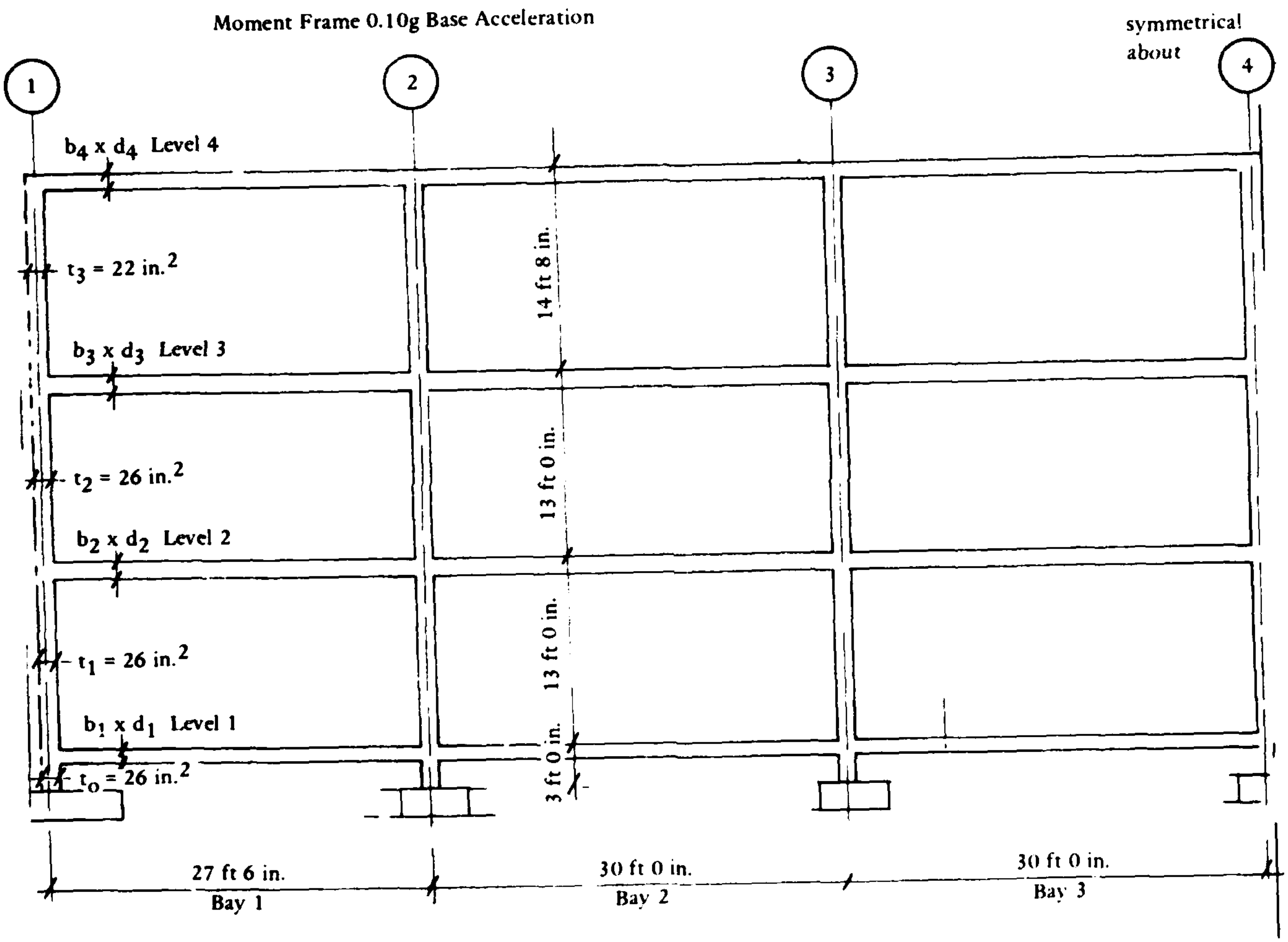

Figure 18. Exterior frame elevation.

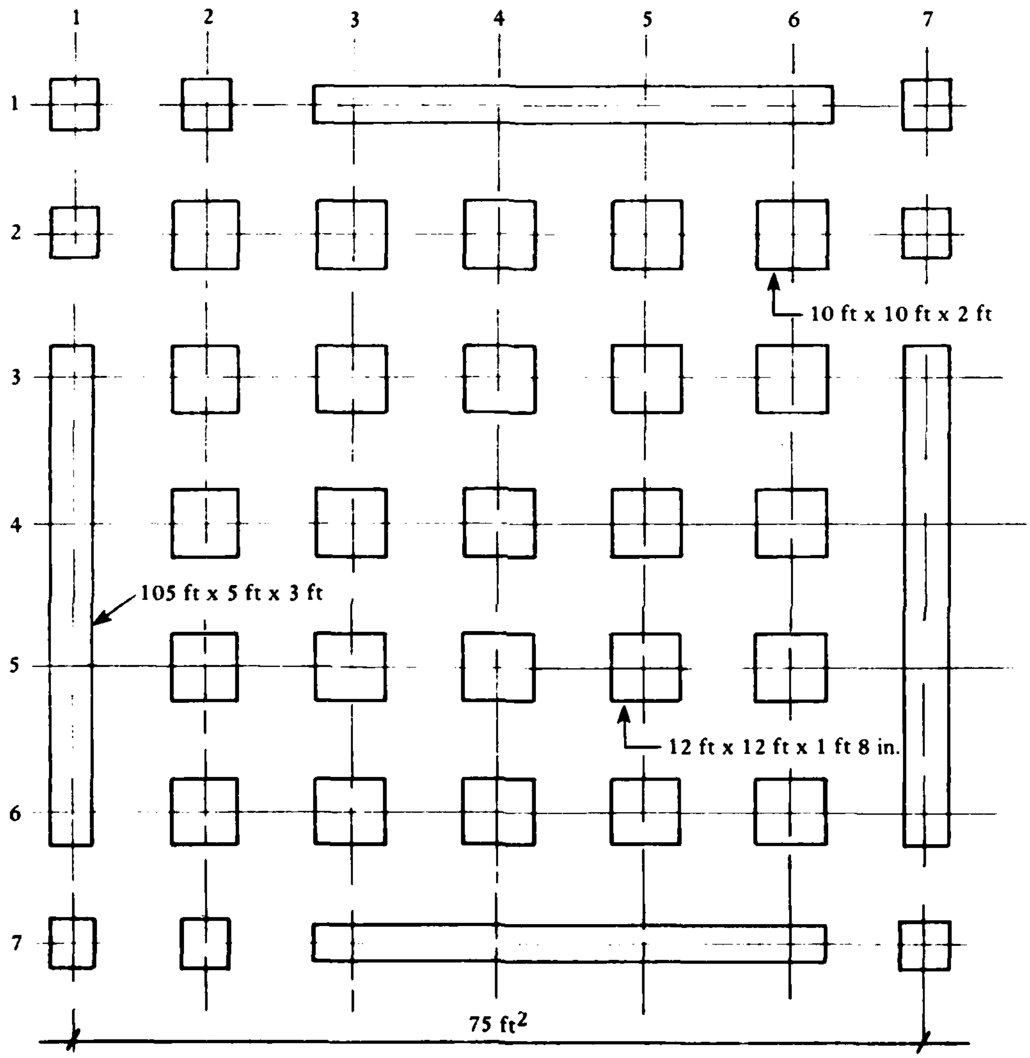

Figure 19. Foundation plan for shear panel 0.25–0.35g base acceleration.

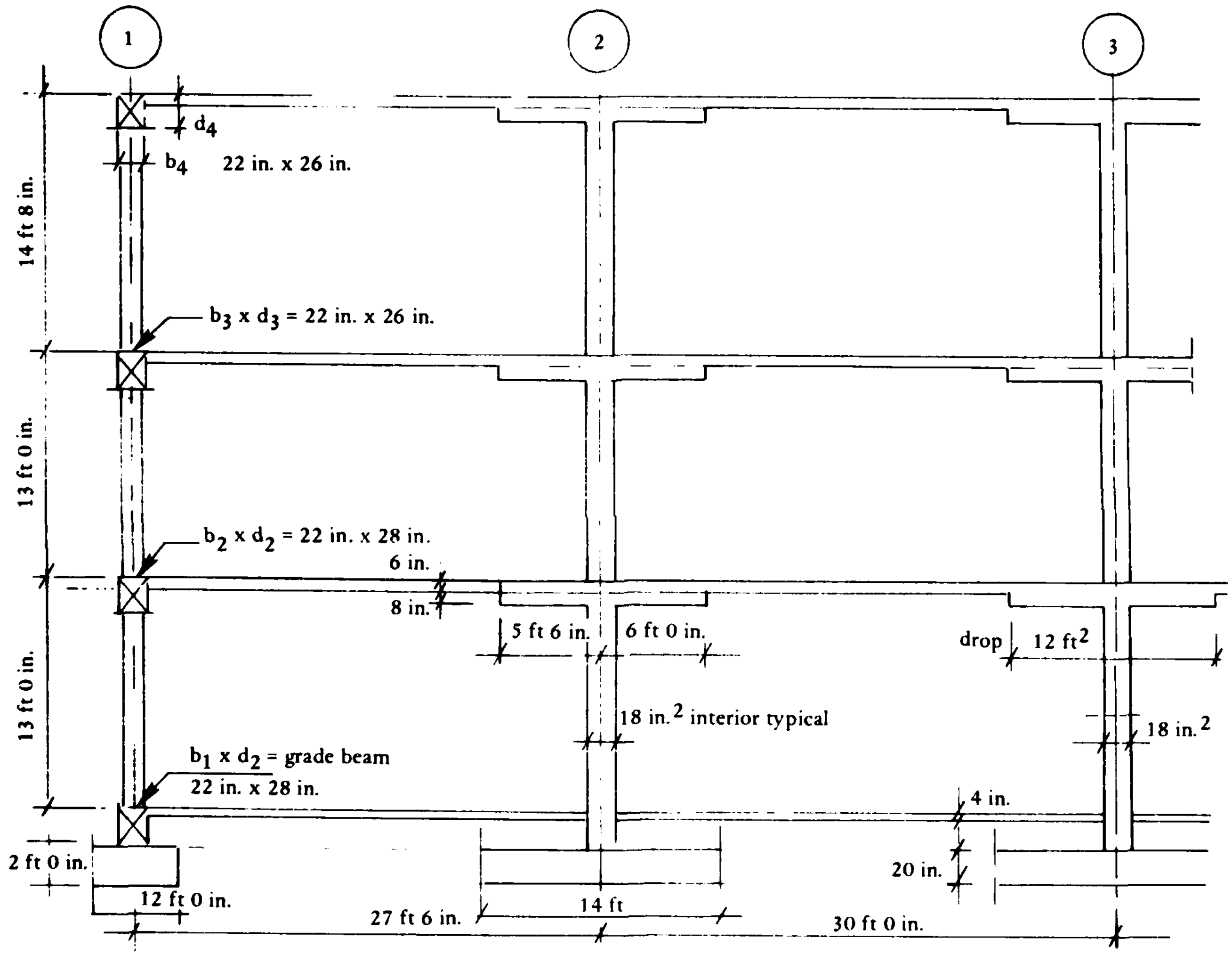

Figure 20. Typical section.

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